

Formulating Dairy Rations



Using Fiber and Carbohydrate Analyses to Formulate Dairy Rations

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Introduction

Carbohydrates are important in the nutrition of animals because they are the major source of energy and typically comprise 70 to 80% of the diet. Cell walls are a major fraction of carbohydrates that have critical roles in plants and in animal diets. In plants, cell walls provide structural support and protection. These functions require that they be sturdy and resistant to destruction, characteristics that limit their digestion by animals. In fact, animals do not produce the enzymes necessary to digest cell walls but have developed a mutually beneficial relationship with microorganisms that do. Bacteria can degrade cell walls, but the process is relatively slow (taking hours or days). Cattle and other ruminants have a unique digestive system that allows them to maximize the digestion of plant cell walls. Ruminants swallow relatively large particles because they chew minimally during eating. These large particles, containing mostly cell walls, are selectively retained in the rumen until they are regurgitated and ruminated. Thus, the ruminant digestive system provides the extra time necessary for bacteria in the rumen to digest the carbohydrates in plant cell walls.

In grazing systems with ruminants of low production, plant walls may comprise 70 to 90% of the carbohydrates consumed. Because cell walls are slowly and incompletely digested, they must be limited in the rations of high producing ruminants, but they still comprise 40 to 60% of the carbohydrates in the diet. The amount of plant cell walls in the diets of ruminants and the

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limitations they impose on the intake and digestion of rations for dairy cows indicate the relevance of research on cell wall utilization. Discovering the relationships between the chemical nature of cell walls and their digestion will help us to understand and remove the limitations they impose on the diets of dairy cows and permit forages to be used more efficiently and in greater quantities. The Cell Wall Characterization and Utilization Work Group was formed by scientists at the US Dairy Forage Research Center to focus research efforts on the development, chemical analysis, microbial fermentation, and animal utilization of forage cell walls. In this discussion I will present our research efforts on fiber analysis, development of a system that uses fiber to formulate dairy rations, and recent experiments evaluating fiber as a tool in ration formulation.

Fiber, Cell Walls, and Structural Carbohydrates

Although they are often used interchangeably, cell walls and neutral detergent fiber (NDF) are not identical, in either definition or composition. Cell wall is a term used by botanists, agronomists, and plant physiologists to refer to a specific anatomical component of plants that surrounds the cell. Chemically, cell walls contain pectin, cellulose, hemicellulose, polymeric lignin, phenolic complexes, and some protein. The composition and structure of cell walls provide the structural elements and protection needed by the plant. Thus, cell walls contain the “structural carbohydrates” of plants, as opposed to the “non-structural carbohydrates,” such as sugars and starches, that are in cell contents and seeds.

In relation to feed composition, fiber is a term used to define a nutritional, not a chemical or anatomical, concept. From the beginning, fiber methods (crude fiber—CF) were designed to measure nutritional entities or components that represented the indigestible ballast in feeds. Because fiber is partially digested, it should be defined more correctly as the indigestible and slowly-digesting, or incompletely available, fraction of the feed that occupies space in the gas-

trointestinal tract (Mertens, 1989). Nutritionally, fiber has both physical and chemical attributes because it is related to both mechanical processes of digestion, such as chewing and passage through the digestive tract, and enzymatic degradation associated with fermentation.

The development of the NDF method was a significant advancement for nutritional characterization of feeds (Mertens 1993). Van Soest (1964, 1967) recognized that an inadequate understanding of the meaning and purpose of fiber prevented the development of methods to replace CF. He used the concept of ideal nutritive entities, which are defined as feed components that have constant true digestibility and endogenous losses, to develop and evaluate the detergent system of fiber analysis. The principle upon which NDF was founded is that feeds can be divided into a readily available soluble fraction and a fibrous residue that is incompletely digested (Van Soest and Moore, 1965). Although NDF does not have ideal properties, neutral detergent solubles (NDS) are almost completely digestible (95 to 98%) and have a constant endogenous loss (11 to 15% of dry matter intake). Van Soest and Wine (1967) developed the NDF method to match the nutritional definition of fiber.

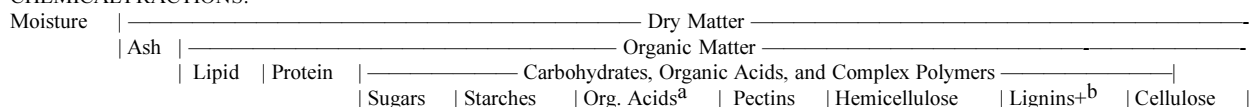
Fiber methods isolate different chemical constituents in feeds (Table 1). The magnitude of CF is less than acid detergent fiber (ADF) which is less than NDF. The use of strong acid and alkali in the CF method leaves a residue that is mostly cellulose with small and variable amounts of lignin and hemicellulose. The ADF method recovers cellulose and most of the polymeric lignin with some contamination from pectin, hemicelluloses, tannin-protein complexes, and ash. Neutral detergent fiber isolates cellulose, lignin, and hemicellulose with some contamination from protein, pectin, and ash. Of the three fiber methods, only NDF measures the three major indigestible or incompletely digestible fractions in plants: hemicellulose, cellulose and lignin. Because ADF does not contain hemicellulose it is not a good estimate of fiber as it is defined nutritionally. It was developed as a preparatory step for the

“The development of the NDF method was a significant advancement for nutritional characterization of feeds (Mertens, 1993).”

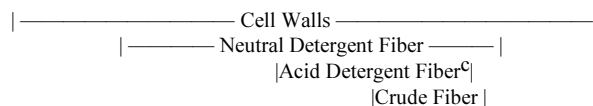
Table 1.

Conceptual partitioning of feeds into chemical and nutritional fractions indicating the relationships among them.

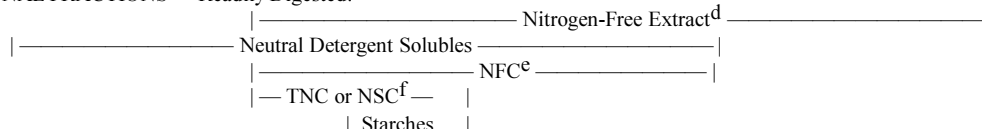
CHEMICAL FRACTIONS:



NUTRITIONAL FRACTIONS — Incompletely Digested:



NUTRITIONAL FRACTIONS — Readily Digested:

^aOrganic acids including the volatile fatty acids in silages and other fermented feeds.^bPolymeric lignins and phenolic acid complexes (some of which may be soluble).^cSome phenolic complexes and lignins with low molecular weight may be solubilized by acid detergent, especially in grasses.^dNitrogen free extract was supposed to represent the readily available carbohydrate in feeds, but does not because it contains some lignins, phenolics, and hemicellulose, especially in forages.^eNon-fibrous carbohydrates determined by difference (100 - Ash - Lipid - Protein - Neutral Detergent Fiber)^fTotal nonstructural carbohydrates (Smith 1969) or non-structural carbohydrates determined analytically.

determination of lignin (Van Soest 1963a, b) and was never intended to be a measure of fiber in feeds.

Cell walls are not an accurate measure of fiber because they contain pectin. Although it is a structural carbohydrate, easily extractable pectin is not fiber, as it is defined nutritionally, because it has a high, relatively constant digestibility. Recent work by Hatfield and Weimer (1995) confirm the observations by Gaillard (1962) that easily extractable pectins are almost completely digestible. Thus, NDF and cell walls are not the same by definition or chemical analysis. Although it can approximate the quantity of cell walls in forages, NDF does not measure cell walls because the majority of the pectin is removed. Differences between NDF and cell walls are important and the terms should be used correctly when discussing and interpreting research findings.

Analysis of NDF

The NDF procedure has a reputation for being more difficult and variable than methods for ADF or CF. The greater variability of NDF analysis is related to three main factors: (1) the multitude of modifications of the method, (2) the magnitude of NDF concentrations, and

(3) problems with dry matter analyses. The last two factors are not related to the NDF procedure, but are related to the effects of scale (magnitude of the measured value). Horwitz (1982) summarized a large number of collaborative studies in which analytical methods were evaluated and observed that the coefficients of variation for analytical methods were related to the mean value of analysis. The equation he developed indicates that expected standard deviation for analyses will be higher for measurements having larger means (e.g., 1.30, .72, and .40 %-units of NDF, ADF and CP, respectively, for a forage containing 60% NDF, 30% ADF, and 15% CP). Thus, variation among NDF analyses will always be greater than for ADF or CP because the value of the measurement is larger.

Errors in determining dry matter (DM) also contribute to the apparent variability in NDF analyses due to the effect of scale when adjusting NDF to a DM basis. If a laboratory measured the DM of a sample to be 94% instead of 89% and the NDF and CP concentrations of the undried sample were 60 and 15%, respectively, the DM adjusted values would be 63.8 vs. 67.4% NDF and 16.0 vs. 16.9% CP, using 94 vs. 89 % DM,

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respectively. Thus, difference in DM determination results in a 3.6%-unit change in NDF compared with only a 0.9%-unit change in CP. Thus, variation in DM determinations among laboratories increases the variation that is often attributed to the NDF method.

Although NDF analyses have larger standard deviations simply as a function of scale, the more important and controllable source of variation in NDF results among laboratories is due to differences in methods. We have been working with the National Forage Testing Association (NFTA) to identify and reduce the variation in forage DM and NDF analyses among laboratories. Although the concept of fiber is based on nutritional criteria, in reality, the measurement of fiber is defined by the method. Modifications of the NDF method affect the “fiber” being measured, cause values to be different, and gives the impression that NDF cannot be measured accurately or precisely.

Difficulties with the NDF method are associated with filtering and washing the fiber residues. Residual starches, pectins, gums, and oils can result in gummy or gelatinous residues that plug the pores of filter vessels and cause problems during filtration which can lead to inaccurate results. The original NDF method (Van Soest and Wine 1967; Goering and Van Soest 1970) used EDTA to chelate calcium, which disrupts the pectin-calcium complex and

solubilizes pectin in boiling solutions. However, the combination of detergent, ethylene glycol (which has been replaced with triethylene glycol), and boiling temperature did not adequately remove starch from feeds. Robertson and Van Soest (1980) and Van Soest et al. (1991) used a heat-stable and detergent-stable amylase to remove starches. They also eliminated sodium sulfite from the original method because it might remove phenolic compounds thought to be lignin.

To solve some of the problems associated with filtering and washing fiber residues and to develop a standard method, we evaluated the effects of source and standardization of heat-stable amylase, timing of amylase addition, amount of sample, particle size during preparatory grinding, porosity and type of filtering vessel and filter aids, filtering technique, weighing methods, use of sodium sulfite, and pH of detergent solutions on NDF analyses. The NDF method we developed uses two additions of heat-stable amylase to remove starch, reduces the amount of sample and neutral detergent solution to .5 g and 50 ml, respectively, and standardizes the residue washing procedure. It requires that the activity of amylase in neutral detergent be standardized, and a method was developed to accomplish this. Our amylase-treated NDF (aNDF) method differs from the original NDF procedure (Van Soest and Wine 1967) in that heat-stable amylase is used to remove starch. It differs from the neutral detergent residue (NDR) method of Robertson and Van Soest (1980) in that the use of sodium sulfite to remove protein contamination was retained.

Our studies (Hintz et al., 1995) suggest that most of the material removed by the inclusion of sodium sulfite in the NDF procedure is proteinaceous and that this material is a potential contaminant of fiber and lignin (Table 2). Removing sodium sulfite from the NDF procedure results in an overestimation of the fiber content of animal byproducts or feeds that have been heated or cooked. It has been argued that fiber analysis of animal byproducts is not appropriate because they do not contain plant cell walls. But this argument is incorrect

Table 2.
Effect of sodium sulfite addition on aNDF values and their nitrogen contents.

Sample	--- % aNDF ---		--- % N in aNDF ---		% CP equivalent of extracted matter
	without sulfite	with sulfite	without sulfite	with sulfite	
Fish meal	30.4	6.3 ^a	5.5	3.3	37.8
Brewer's grains	52.3	40.9	3.7	1.8	65.6
Distiller's grains	38.6	27.9	4.6	2.1	68.8
Meat scraps	30.8	22.2 ^a	8.2	6.0	85.1
Soybean meal	18.5	12.4	3.1	0.6	52.1
Bromegrass	66.6	64.2	0.6	0.5	24.2
Ladino clover	31.9	30.3	1.5	0.9	78.2
Alfalfa silage	43.6	42.2	0.9	0.6	76.3
Corn silage	36.1	34.7	0.3	0.2	16.6
Corn grain	11.4	10.1	1.5	1.2	24.3
Alfalfa hay	45.5	44.3	0.9	0.6	70.9
Citrus pulp	21.3	20.2	1.6	1.3	43.9

^aMost of the aNDF in these feeds is ash from bone.

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“It has been proposed that dairy rations be balanced for the more readily available carbohydrates ...”

because fiber (as opposed to cell walls) is a nutritional entity that can exist in all feeds. Therefore, any method for fiber analysis should correctly measure the indigestible and slowly-digesting fraction of the feed that occupies space in the gastrointestinal tract irrespective of the feed type or source. Any replacement for CF as the official indicator of fiber in manufactured feeds must be appropriate for all feeds.

The aNDF method is described in the procedures manual of the NFTA (Undersander et al. 1993). This method solves many of the difficulties in determining aNDF and can be used on all feeds. In addition, we have developed modifications of the routine method that can accommodate the analysis of difficult samples (Mertens 1991). Based on our experience and that of the certification program of the NFTA, clients should expect 95% of the labs analyzing a subsample of the same forage to obtain an aNDF value within ± 2.0 % units of the true reference value.

Sugars, Starches, Non-structural and Non-fiber Carbohydrates

As is the case with cell walls and fiber, the terminology associated with the non-cell wall carbohydrates is confusing. Theoretically, readily available carbohydrates can be calculated by subtracting ash, ether extract (EE), and crude protein (CP) from NDS. This approach was used when calculating inputs for a rumen model to insure that all major fractions with distinct nutritional attributes summed to 100% of DM (Mertens, unpublished 1980). Mertens (1988) suggested that this approximation of readily available carbohydrates ($100\% \text{ DM} - \% \text{ CP} - \% \text{ EE} - \% \text{ Ash} - \% \text{ NDF}$) be called non-fibrous carbohydrate (NFC) to indicate its origin. He demonstrated that NFC is different from total nonstructural carbohydrate (TNC) that is determined by analytical methods (Smith 1969). Unfortunately, the terms nonstructural carbohydrates (NSC), TNC, and NFC are being used interchangeably by nutritionists and analytical laboratories. As illustrated in Table

1, it is clear that NFC, calculated by difference, does not contain the same components that are determined by NSC or TNC methods. Both pectins and organic acids, including the volatile fatty acids (VFA) in fermented feeds, are included in NFC; but are not included in TNC or NSC. To avoid confusion, terminology should be standardized to indicate that NFC is calculated by difference using fiber analysis and TNC or NSC is determined analytically.

Non-fibrous carbohydrate is a crude estimate of total, rapidly fermented, nonprotein organic matter in feeds, with the exception of organic acids which probably do not contribute to microbial protein or VFA production. Because pectins are fermented to acetic acids and organic acids are not fermented appreciably in the rumen, NSC may provide a better estimate of the carbohydrates that are fermented to propionic acid, can alter microbial populations, and may result in lower ruminal pH. However, the starch in corn and sorghum is not rapidly fermented when in the dry, coarsely ground or cracked form. Thus, effects of processing and source of the starch need to be taken into account to most accurately use NSC to indicate ruminal fermentation.

It has been proposed that dairy rations be balanced for the more readily available carbohydrates (Hoover et al. 1990 and Nocek and Russell 1988). Formulating rations for starch, NSC, TNC, or pectin concentration may provide independent information that is useful in formulating dairy rations, but no requirements or limits for these constituents have been defined and they are difficult to measure in feeds. Currently, there are no simple and accurate methods for determining starch, NSC, TNC, or pectin. Mertens (1992) has shown, using tabular values, that starch might be useful in formulating rations when used in conjunction with aNDF to define the upper limit for the grain content in low forage rations. However, the practical result of balancing rations for NFC is that rations are actually being balanced for aNDF because NFC and aNDF are not independent measurements. Concentrations NFC and aNDF are almost perfectly inversely related because DM

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“Intake is a function of both animal and dietary characteristics ...”

must sum to 100% and the concentrations of CP, EE, and ash are relatively constant among dairy rations. Thus, there appears to be no advantage to formulating rations for NFC, and the use of aNDF is preferred because it is measured directly.

Using Fiber to Formulate Dairy Rations

Even among high-producing dairy herds, there is great diversity in rations that can be successfully fed to dairy cows. A useful ration formulation system should define the upper and lower boundaries for ration characteristics and allow the nutritionist or farmer the opportunity to select the most profitable, effective, and efficient ration that is possible for each specific locale and situation of feed availability and price. Fiber concentration in the diet of dairy cows has been related to intake regulation, digestibility, rate of passage, and chewing activity. If rations are too high in fiber, energy density of the ration is low, fill limits intake, and animal performance (milk production and tissue balance) declines. If rations are too low in fiber, ruminal fermentation is suboptimal, acidosis and off-feed disorders occur, and animal performance and health suffer.

Mechanisms of Intake Regulation

The NDF-Energy Intake System for formulating dairy rations is based on the concept that feed intake by animals is regulated by two mechanisms (Mertens 1985, Mertens 1987). When high energy, low fiber rations are fed, cows regulate energy intake ($I_e \times E$) to meet their energy requirement (R). This mechanism can be described by a simple equation that can be solved for intake: $I_e \times E = R$, $I_e = R/E$; where I_e is intake regulated to meet energy demand (kg DM/d), R is the energy requirement (Mcal/d) and E is the energy density of the ration (Mcal/kg).

When high fiber, low energy rations are fed, intake of dairy cows is limited by the filling effect of the diet ($I_f \times F$) so that it equals their capacity (C) to process fiber through the digestive tract. This mechanism can be described by a simple equation that can be solved for intake:

$$I_f \times F = C,$$

$$I_f = C/F;$$

where I_f is intake limited by fill (kg DM/d), C is the fill capacity of the animal (L/d) and F is the filling effect of the ration (L/kg).

Because energy density (E) and fill (F) are inversely related to each other, these two mechanisms of intake regulation form a system of two intersecting curved lines. Predicted intake (I_p) will result from whichever mechanism of intake is most limiting for a given level of production and fill effect in the diet, i.e., $I_p = \min(I_e, I_f)$. Intake is maximized for a specific level of milk production at the point the two lines cross because this defines the ration that has the highest filling effect but still meets the animals requirement for energy without creating excessive distention of the gastrointestinal tract or requiring compromises in production or use of body reserves. Thus, I_{\max} occurs when $I_e = I_f$ or when $R/E = C/F$.

These simple equations illustrate several interesting properties about intake regulation that can be used to formulate rations.

1. Qualitative theories of intake regulation, which are commonly accepted, can be defined by mathematical equations that have direct quantitative consequences, such as indicating that rations exist that maximize intake and fill while meeting the energy demands of the animal.
2. Intake is a function of both animal and dietary characteristics and that any empirical equation or simulation model that does not include both animal and dietary factors to predict intake cannot have universal application.
3. Animal attributes (R and C) are fluxes or flows because they are expressed per unit of time. This

Table 3.

Intakes of NDF that maximize animal performance during the lactation cycle for cows in first or second and greater lactations.

Week of Lactation	First Lactation	≥Second Lactation
	(-- % body weight per day --)	
2	.78	.87
4	.91	1.00
8	1.05	1.17
12	1.12	1.26
16	1.14	1.29
20	1.14	1.30
24	1.13	1.27
28	1.11	1.24
32	1.08	1.19
36	1.04	1.13
40	1.01	1.08
44	.97	1.01
Dry Cows	.92	.95

means that fill capacity is not a pool, such as ruminal dry matter, but a volume of matter that can be processed per day.

- Intake is related to the reciprocal of dietary characteristics, whereas it is linearly related to animal attributes.
- Simple linear correlations are inappropriate to evaluate the effectiveness of feed characteristics for predicting intake because the functional relationship is both curvilinear and discontinuous.
- Characteristics of the ration (fill and energy density) must change as the requirement or capacity of the animal changes. This last point is the basis for the NDF-Energy Intake System.

Maximum Fiber Rations and the NDF-Energy Intake System

Because NDF is related to the filling effect and the energy density of feeds, it can be used to relate the two mechanisms of intake regulation on a common scale (Fig. 1). The NDF-Energy Intake System uses NE_L (NRC, 1989) to represent energy requirements and energy density of the diet, NDF as a proxy for the filling effect of the diet, and NDF intake (NDFI) as an indicator of the fill processing capacity (daily flux) of the animal. The objective of the NDF-Energy Intake System is to determine the forage to concentrate ratio of the ration that maximizes intake and NDF concentration, while meeting the energy requirements for a target level of milk production.

The formulas used to calculate the maximum forage ration using the NDF-Energy Intake System have been presented in several publications (Mertens 1987, 1992). The system also can be adapted to linear programming so rations can be formulated simultaneously for NDF, NE_L , absorbed protein, and minerals (Mertens and Dado 1993). One of the main factors affecting the flux of NDF through the animal is particle size. Finely ground NDF will not have the same effect on fill as long forage fiber. Therefore, the NDF of ground, high-

fiber byproduct feeds should be adjusted to reflect this difference. An approach for adjusting NDF for differences in fill associated with particle size has been proposed, and NDF, fill adjusted NDF (ANDF), and carbohydrate composition of feeds have been provided by Mertens (1992).

In addition to the NDF concentration of forages and concentrates used in the ration, the rations formulated using the system depend on the NDFI constraint (NDFIC) of the animal. In a series of experiments, we observed that the production of 4% fat-corrected milk was maximized for cows in mid to late lactation when the NDFIC was 1.25% of body weight per day. A more detailed analysis of published data from cows in other stages of lactation indicates that NDFIC is different for first lactation and older cows, and it varies over the lactation cycle (Table 3). The NDFIC in Table 3 are based on actual body weights of cows as they change during lactation. It is recommended that the NDFIC be lowered by one standard deviation (0.1% BW/d) to insure that at least 85% of the animals in a group can achieve the fill constraint.

As milk production and intake increases, the system predicts that the NDF concentration of the diet that maximizes the fill of the cow will decrease (Fig. 1, points M_{50} , M_{40} , and M_{30}). Conversely, when cows of different milk production potentials (due to stage of lactation or genetic potential) are fed a ration that is low in NDF relative to their energy needs, they will have different intakes (Fig. 1, points M_{50} , P_{40} , and P_{30}). The observation that cows fed rations with the same NDF concentration do not have the same intake does not negate the value of using NDF to formulate rations and does not indicate that NDF is unrelated to intake (as suggested by low linear correlation coefficients between NDF and intake), but serves to illustrate that the relationship between NDF and intake is complex and depends not only on NDF, but also on the milk production potential of the cow.

The NDF-Energy Intake System has been criticized for being too simple, being discontinuous (with threshold breakpoints), and assuming that all NDF

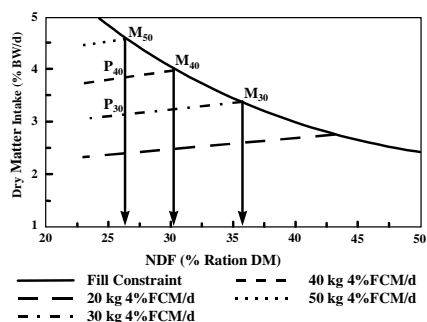


Figure 1. Predictions, using the NDF-Energy Intake System, of intakes for cows with milk production potentials of 30, 40, and 50 kg/d of 4% fat-corrected milk (FCM) when forage content of the ration is maximized (M_{30} , M_{40} , and M_{50} , respectively) and when given a single ration formulated for cows producing 50 kg/d (P_{30} , P_{40} , and M_{50} , respectively).

“Simplicity is a desirable property of a system unless it fails to mimic reality.”

“... the first priority of a ration formulation system should be to determine the forage to concentrate ratio that yields the optimal NDF concentration in ration.”

“Differences among NDF sources can be incorporated into the NDF-Energy Intake System as new research becomes available.”

acts alike in dairy rations. Simplicity is a desirable property of a system unless it fails to mimic reality. One of the strengths of the NDF-Energy Intake System is that it provides logical and realistic estimates of the maximum forage to concentrate ratio in rations for cows of different production potentials when fed forages that differ in nutritive value using a simple model of intake regulation and routinely measured feed characteristics. The use of threshold breakpoints to define the point at which fill and energy equally affect intake may not represent the intake control system in cows. However, it is the simplest control mechanism to implement and until it is shown to be inadequate for formulating dairy rations, it should not be rejected based on philosophical principle. Just because smooth curvilinear lines can be drawn through animal data does not prove that animal physiological control mechanisms obey an intrinsic law of curvilinearity.

It cannot be denied that the filling effect of NDF varies among sources depending on their density, digestion rate, extent of digestion, and rate of passage. By definition, fiber represents the fraction of feeds that has the most variable nutritive value. However, before variation among NDF sources is used to discredit the use of NDF as a tool for formulating dairy rations, the variation among fiber sources in a ration at the same NDF concentration must be compared with variation associated with different levels of NDF in rations. A ration consisting of alfalfa hay, corn silage, corn, and soybean meal that contains 32% NDF will have about 66.3% TDN with an NDF digestibility of approximately 41%. Increasing NDF digestibility by 10% (to 45%) would increase the ration TDN concentration to 67.5% (1.68 Mcal NE_L/kg). Reducing the ration NDF from 30 to 28% by altering the forage to concentrate ratio will also obtain a ration with 67.4% TDN (1.67 Mcal NE_L/kg). In most cases it is easier to alter forage to concentrate ratio than obtain fiber sources with superior intake and digestibility potential. Thus, it appears that the first priority of a ration formulation system should be to

determine the forage to concentrate ratio that yields the optimal NDF concentration in ration.

The primacy of NDF concentration in the ration over differences among NDF sources does not mean that differences in cell walls are irrelevant. Once the correct concentration of NDF is established in the ration, the factor most limiting the utilization of the diet is characteristics of cell walls. The limitations imposed by other components in the diet, such as protein, NFC, minerals, and vitamins, can usually be eliminated by proper ration formulation. However, the innate limitations associated with forage cell wall utilization cannot be solved by formulation but can be alleviated only by understanding and altering the characteristics of cell walls.

The NDF-Energy Intake System is not intended to replace practical wisdom about feeding and differences among feeds. Rather, it is proposed as a first step in developing a quantitative method for insuring that differences in the fiber concentration of feeds, especially forages, are taken into account when formulating dairy rations. Formulating rations for NDF insures that a forage to concentrate ratio in the diet is obtained that accommodates differences in forage quality and provides the cow with the proper balance of readily digestible and slowly digestible nutrients in the diet at an intake the animal can attain. Differences among NDF sources can be incorporated into the NDF-Energy Intake System as new research becomes available.

In hot climates and in some situations of high milk production targets, it may be desirable to feed fat as oil seeds, animal fat, or commercial products. These diet modifications can be incorporated easily into the NDF-Energy Intake System by increasing the NE_L value of the concentrate portion of the ration to reflect the energy density of the added fat. Adding fat or fat-containing feeds that contain little fiber can allow rations to be formulated using lower quality forage and still meet target milk productions. Alternatively, the NDF-Energy Intake System predicts that more forage of a given quality can be included in the

Table 4.

Rations with maximum fill adjusted NDF (ANDF) that meet milk production and tissue balance requirements for mature cows weighing 650 kg and producing 45 kg/d of milk containing 3.5% fat at peak lactation when fed alfalfa of different qualities (Mertens, 1995a).

Ration characteristic	Alfalfa = 39% aNDF		Alfalfa = 42% aNDF		Alfalfa = 46% aNDF	
	w/o CS ^a	w/ CS	w/o CS	w/ CS	w/o CS	w/ CS
Forage (%)	64.2	60.5	55.1	51.2	48.3	44.4
Ration ANDF (%)	28.7	29.3	28.5	29.3	28.4	29.3
Predicted DM intake (kg/d)	26.0	25.5	26.2	25.5	26.3	25.5

^aWithout or with 15% cottonseed in the concentrate.

“To insure that adequate long fiber is included in rations with minimum forage, it was suggested that 75% of the NDF in the ration come from forage and that the ration contain at least 25% NDF.”

ration when low-fiber fat sources are used, but that intake will be reduced slightly. When high fiber sources of fat are fed, the system adjusts the ration for the effects of increased fat and fiber in the concentrate. The NDF-Energy Intake System suggests that when 15% cottonseed is added to the concentrate, the proportion of alfalfa and expected intake would be decreased for each quality of forage (Table 4). When cottonseed is fed, the proportion of alfalfa in the ration is reduced to balance the fiber supplied by the cottonseed. However, the largest changes in rations are due to differences in forage quality. As shown in Table 4, the fraction of forage in the total ration decreases as the NDF content of the alfalfa increases, which demonstrates the value of using the NDF system to adjust dairy rations for differences in forage quality. A 3%-unit reduction in the aNDF in alfalfa results in a 7 to 9%-unit increase in the proportion of forage in the ration.

tain a desirable ruminal environment as indicated by adequate chewing activity. Not only is the level of NDF in the diet important, but also the size of the fiber particles is critical for stimulating chewing activity and obtaining a ruminal environment that is efficient and effective.

To insure that adequate long fiber is included in rations with minimum forage, it was suggested that 75% of the NDF in the ration come from forage and that the ration contain at least 25% NDF (Mertens 1985, 1987). Mertens (1992) proposed the concept of roughage value (RV) to represent the feed's ability to stimulate chewing by the animal. Like ANDF (which adjusts NDF for differences in filling effect), RV is based on NDF that is adjusted for particle size, although the adjustment factor differs from that used for ANDF. Balancing rations for RV or physically effective NDF insures optimal rations when high-fiber byproduct feeds or fiber sources such as cottonseed hulls are used as roughages. Research is in progress to develop a system for classifying the particle size of feeds and to determine the physical effectiveness factors for each particle classification based on observed chewing activities. Because starch concentrations of rations may be too high when they contain minimum RV which can lead to acidosis, it may be desirable to include a maximum starch constraint for these rations (Mertens 1992).

By combining the minimum requirement for fiber in dairy rations with the maximum fiber estimated using the NDF-Energy Intake System the total population of feasible rations for dairy cows can be defined (Fig. 2). The system indicates that the number of feasible

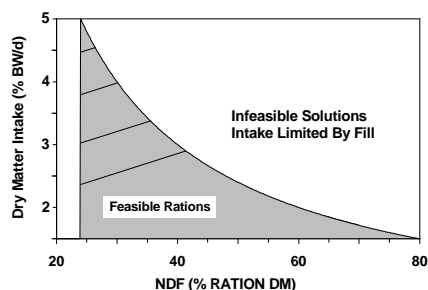


Figure 2. The NDF-Energy Intake System identifies the area of feasible solutions for dairy rations in which intake is not limited by fill, but by the cow's energy demand.

Calculating Minimum Forage Contents in Dairy Rations

As milk production increases, the amount of forage that can be fed decreases and approaches the minimum forage that can maintain ruminal function. In addition, when grains are more economical than forages, it is most profitable to feed minimal forage. In these situations, the objective of ration formulation is to meet the minimum fiber requirement which insures that ruminal function and animal health are maintained. The critical requirement in minimum forage rations for dairy cows is to provide the minimum amount of fiber needed to main-

rations decreases as milk production and dry matter intake increases (Fig. 2). The system also predicts that forage quality and feeding of fats become more critical in attaining adequate energy intakes when production exceeds 45 kg of 4% fat-corrected milk per day.

Evaluating the NDF-Energy Intake System

Mertens (1994) used a summary of published data to demonstrate that intakes predicted by the system correspond to those observed in a wide variety of experimental diets and conditions. We have also conducted several experiments to test the system directly. In one experiment (Mertens 1995b), sixty Holstein cows, averaging 90 days in lactation and 35.1 kg milk/d, were assigned to one of five rations containing either sorghumXsudan hybrid, orchardgrass, alfalfa, wheat, or corn silage. Total mixed rations contained 8% roasted soybeans and were formulated to have 31% aNDF and 18% CP using high moisture corn and soybean meal. Although forage to concentrate ratio varied from 42:58 to 64:36 among the forages, there was little difference in intake or milk production among forage sources when rations contained similar aNDF (Table 5). Intake of aNDF varied from 1.10 to 1.25% BW/d. This study suggests that forages of differing qualities can result in equal performance if fed in rations that contain similar aNDF.

Another study (Mertens and Halevi 1995) was designed to test the NDF-

Energy Intake System during a complete lactation cycle and compare it to rations formulated to contain constant forage to concentrate (F:C) ratios using forages that varied from 100% alfalfa to 100% corn silage. Seventy-two cows were blocked by calving date, parity, and 305-d mature equivalent milk production and assigned to one of six treatments: alfalfa silage (AS), 2/3 AS+1/3 corn silage (AC), 1/3 AS+2/3 corn silage (CA), corn silage (CS), alfalfa silage with increasing F:C ratio throughout lactation (FC), and AC fed at a constant 27% aNDF throughout lactation (27). Rations were formulated to contain a minimum of 18% CP and 27, 31, 35, or 39% aNDF using AS, AC, CA, or CS with high moisture corn, soybean meal, heated soybeans, and urea.

Cows were fed a covariate ration for the first three weeks of lactation and then switched to their respective treatments and fed rations containing 27% aNDF for 12 weeks. After 12 weeks, the NDF-Energy Intake System was used to determine the recommended aNDF concentration of the diet that would maximize production and forage intake for each cow during each week of lactation. Cows on treatments AS, AC, CA, and CS were fed rations containing 27, 31, 35, or 39% aNDF based on these calculations. Cows on FC were similarly assigned diets containing 50, 60, 70, or 80% forage.

Each group of cows had 25% first-lactation and 25% second-lactation cows. Each treatment had cows that peaked at 55 kg of milk/d. Milk productions for the first 273 days of lactation were 8450 kg (18590 lb), 8470 kg (18630 lb), 8350 kg (18360 lb), 8370 kg (18420 lb), 8290 kg (18240 lb), and 8750 kg (19250 lb) for treatments AS, AC, CA, CS, FC, and 27, respectively. These totals were not adjusted for differences in covariate milk production of 37.5, 37.4, 38.3, 38.4, 37.5, and 35.5 kg/d, respectively, for treatments AS, AC, CA, CS, FC, and 27. There was little difference in milk production, milk fat percentage, or milk protein percentage among forage sources when fed in rations containing similar aNDF.

“... forage quality and feeding of fats becomes more critical in attaining adequate energy intakes when production exceeds 45 kg of 4% fat-corrected milk per day.”

Table 5.
Production responses of dairy cows fed silage-containing rations with similar aNDF concentrations.

Variable	Sorghum				
	X sudan	Orchardgrass	Alfalfa	Wheat	Corn
Silage CP	12.8	15.5	17.2	10.2	8.3
Silage aNDF (ash-free)	54.8	48.4	45.2	54.4	41.6
Forage in ration (% DM)	42.2	51.5	57.2	43.6	63.6
Ration NDF (% DM)	31.0	31.1	31.4	30.3	30.5
Dry matter intake (kg/d)	22.0	23.3	23.6	22.7	22.0
Milk production (kg/d)	32.4	33.7	33.6	33.5	34.6
Milk fat (%)	3.6	3.8	3.6	3.4	3.5

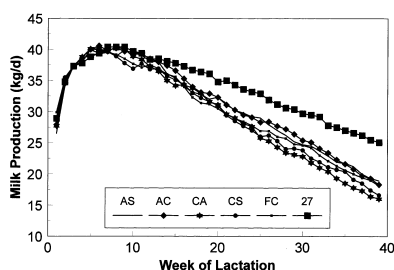


Figure 3. Lactation curves of cows fed alfalfa silage (AS); 2/3 AS + 1/3 corn silage (AC); 1/3 AS + 2/3 corn silage (CA); corn silage (CS) in rations containing 27, 31, 35, and 39% aNDF; AS in rations containing 50, 60, 70, and 80% forage (FC); or AC in a ration containing 27% aNDF throughout the lactation (27). Curves were adjusted to the same production at covariate week 3 of lactation.

“Carbohydrates are an important component in dairy rations that provide the majority of energy for cows ...”

The shape of the lactation curve was different for treatment 27 compared to all other treatments when adjusted to the same covariate milk production at week 3 (Fig. 3). It appears that the NDFIC recommendations given in Table 3 may overestimate the maximum fiber cows can consume after peak lactation (which maximizes milk production and tissue balance) because cows fed rations increasing in aNDF during lactation did not attain the production of the positive control (treatment AC fed at the level of 27% aNDF throughout lactation). We are analyzing the data to refine estimates of NDFIC in Table 3 which may need to be reduced by 5 to 10%. Part of the discrepancy may relate to changes in the NDF procedure. The aNDF method used during this experiment results in fiber values that are 5 to 10% lower than NDF methods that do not include sodium sulfite which were used to develop the values reported in Table 3.

Conclusions

Carbohydrates are an important component in dairy rations that provide the majority of energy for cows, but also comprise the feed fractions which limit intake and digestibility. Because they vary tremendously in nutritive availability and their effects on ruminal function and intake, analysis of carbohydrates is a critical element in determining their role in ration formulation. Although the terms are often used interchangeably, plant cell walls and neutral detergent fiber represent different approaches to carbohydrate classification and analysis. Fiber is a nutritional term that defines the indigestible and slowly digesting fractions of feeds that occupy space in the gastrointestinal tract. The amylase-treated neutral detergent fiber method solves most of the problems associated with fiber analysis and can be a useful tool for ration formulation.

The NDF content of feeds when adjusted for differences in filling effect and physical effectiveness can be used to determine the maximum and minimum fiber in dairy rations. It provides an excellent tool for evaluating the fiber, carbohydrate, and energy characteristics of feeds and rations. Because aNDF

separates feeds into NDF and NDS, it identifies the major differences among feeds and allows them to be described on a single continuum. We plan to continue to build on the foundation of detergent fiber analysis as the basis for formulating rations for dairy cows that are more effective, efficient, and profitable. New systems will be based on input:output response functions that use more sophisticated models to relate dairy cow performance to the characteristics of fiber in dairy rations.

References

- Gaillard, B.D.E. 1962. The relationship between the cell-wall constituents of roughage and the digestibility of the organic matter. *J. Agric. Sci.* 59:369.
- Goering, H.K., and P.J. Van Soest. 1970. Forage Fiber Analyses (Apparatus, reagents, procedures, and some applications). USDA-ARS Agric. Handbook No. 379. US Govt. Printing Office, Washington, DC. 20 pp.
- Hatfield, R.D., and P.J. Weimer. 1995. Degradation characteristics of isolated and in situ cell wall lucerne pectic polysaccharides by mixed ruminal microbes. *J. Sci. Food Agric.* 69:185-196.
- Hintz, R. W., D.R. Mertens and K.A. Albrecht. 1995. Effects of sodium sulfite on recovery and composition of detergent fiber and lignin. *J.A.O.A.C.* 78:16-22.
- Hoover, W.H., S.R. Stokes and T.K. Miller. 1990. Interactions of proteins, carbohydrates in rumen explored. *Feedstuffs* 62(April 16):17.
- Horwitz, W. 1982. Evaluation of analytical methods used for regulation of foods and drugs. *Anal. Chem.* 54:67A-76A.
- Mertens, D.R. 1985. Factors influencing feed intake in lactating cows: from theory to application using neutral detergent fiber. *Proc. Georgia Nutr. Conf.* p. 1-18.
- Mertens, D.R. 1987. Predicting intake and digestibility using mathematical models of ruminal function. *J. Animal Sci.* 64:1548-1558.
- Mertens, D.R. 1988. Balancing carbohydrates in dairy rations. *Proc. Large Herd Dairy Mgmt. Conf., Dept. Animal Sci., Cornell Univ., Ithaca, NY*, p. 150-161.
- Mertens, D.R. 1989. Fiber analysis and its use in ration formulation. *Proc. 24th Pacific NW Anim. Nutr. Conf. (R.G. Bull, B.J. Hawk and K.K. Dickinson, eds.)* p. 1-10.
- Mertens, D.R. 1991. Critical conditions in determining detergent fibers. *Proc. National Forage Testing Assn. Forage Analysis Workshop* p. 5-11.
- Mertens, D.R. 1992. Nonstructural and structural carbohydrates. In *Large Dairy Herd Management* (H.H. Van Horn and C.J. Wilcox, eds.). *Am. Dairy Sci. Assoc., Champaign, IL*. p. 219-235.
- Mertens, D.R. 1993. Importance of the detergent system of feed analyses for improving animal nutrition. *Proc. Cornell Nutr. Conf.* p. 25-36.
- Mertens, D.R. and Dado, R.G. 1993. System of equations for fulfilling net energy and absorbed protein requirements for milk component production. *J. Dairy Sci.* 76:3464-3478.
- Mertens, D.R. 1994. Regulation of forage intake. In *Forage Quality, Evaluation, and Utilization* (G.C. Fahey, Jr., ed.). *Am. Soc. Agron., Madison, WI*, p. 450-493.

- Mertens, D.R. 1995a. Fiber evaluation and utilization for dairy cattle feeding programs. California Anim. Nutr. Conf., Sacramento. p. 105-122.
- Mertens, D.R. 1995b. Comparing forage sources in dairy rations containing similar neutral detergent fiber concentrations. J. Anim. Sci. 73 (Suppl.1):201.
- Mertens, D.R., and A. Halevi. 1995. Forage sources and ration formulation systems for dairy cows. J. Dairy Sci. 78 (Suppl.1):275.
- Nocek, J.E. and J.B. Russell. 1988. Protein and energy as an integrated system. Relationship of ruminal protein and carbohydrate availability to microbial synthesis and milk production. J. Dairy Sci. 71:2070-2107.
- NRC (National Research Council). 1989. Nutrient requirements of dairy cattle, 6th ed., National Academy of Science, Washington, D.C. 157 pp.
- Robertson, J.B., and P.J. Van Soest. 1980. The detergent system of analysis and its application to human foods. In The Analysis of Dietary Fiber in Food (W.P.T. James and O. Theander, eds.). Marcel Dekker, Inc., NY. p. 123.
- Smith, D. 1969. Removing and analyzing total nonstructural carbohydrates from plant tissue. Wisc. Agric. Expt. Stat. Res. Rep. 41, Madison.
- Undersander, D., Mertens, D.R. and Thiex, N. 1993. Forage Analyses Procedures. National Forage Testing Assoc., Omaha, NE. 154 pp.
- Van Soest, P.J. 1963a. The use of detergents in analysis of fibrous feeds: I. Preparation of fiber residues of low nitrogen content. J. A. O. A. C. 46:825.
- Van Soest, P.J. 1963b. The use of detergents in analysis of fibrous feeds: II. A rapid method for the determination of fiber and lignin. J. A. O. A. C. 46:829.
- Van Soest, P.J. 1964. Symposium on nutrition and forage and pastures: new chemical procedures for evaluating forages. J. Animal Sci. 23:838.
- Van Soest, P.J. 1967. Development of a comprehensive system of feed analysis and its application to forages. J. Animal Sci. 26:119.
- Van Soest, P.J., and L.A. Moore. 1965. New chemical methods for analysis of forages for the purpose of predicting nutritive value. Proc. IX Int'l Grassl. Congr. Sao Paulo, Brazil. Vol. 1:783.
- Van Soest, P.J., J.B. Robertson, and B.A. Lewis. 1991. Methods for dietary fiber, neutral detergent fiber, and nonstarch polysaccharides in relation to animal nutrition. J. Dairy Sci. 74:3583-3597.
- Van Soest, P.J., and R.H. Wine, 1967. The use of detergents in analysis of fibrous feeds: iv. Determination of plant cell-wall constituents. J. A. O. A. C. 50:50.